

Double $c\bar{c}$ production in e^+e^- annihilations at high energy

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We review the current state of experimental knowledge on double $c\bar{c}$ production in e^+e^- annihilation. The large cross-sections ($\mathcal{O}(20\text{ fb})$) for $e^+e^- \rightarrow \gamma^* \rightarrow \psi^{(\prime)} (c\bar{c})_{res}$ processes have been confirmed by detailed tests and reproduced by a second group: they should now be considered well-established. The latest experimental results concern the case where the second $c\bar{c}$ system is above open-charm threshold: hidden-charm states continue to play a prominent role in the mass spectrum. Some “loose ends” in the field are also briefly discussed.

1. Introduction

Electron-positron annihilation to charmonium and an additional hidden-charm state, or a pair of open-charmed mesons — double $c\bar{c}$ production — has been known for only five years, but is now an established object of theoretical and experimental study. The field is still being driven by data. This presentation surveys current experimental knowledge: after reviewing the history (Section 2) and the now-established results on double-charmonium production $e^+e^- \rightarrow \psi^{(\prime)} (c\bar{c})_{res}$ (Section 3), we discuss the latest experimental work, which focusses on states above open-charm threshold (Section 4). Some “loose ends”, which might reward renewed attention, are also noted (Section 5). In closing (Section 6) we summarize both established and new results, and their relation to theory.

2. History

This field grew from studies of inclusive charmonium production $e^+e^- \rightarrow \psi^{(\prime)} X$ [1, 2]. An old CLEO analysis on a small sample [3] had presented evidence for direct decays $\Upsilon(4S) \rightarrow J/\psi X$, distinguished by J/ψ momenta above the endpoint for $\Upsilon(4S) \rightarrow B\bar{B}[\rightarrow J/\psi X]$. Using data from early B-factory running— 29.4 fb^{-1} on the $\Upsilon(4S)$ resonance, and 3.0 fb^{-1} in the continuum 60 MeV below—Belle [1] excluded such production, setting a limit $\mathcal{B}(\Upsilon(4S) \rightarrow J/\psi X) < 1.9 \times 10^{-4}$ at 95% confidence. More importantly, they established picobarn cross-sections for $e^+e^- \rightarrow \psi^{(\prime)} X$ processes in the continuum, and a peculiar momentum spectrum for the produced $\psi^{(\prime)}$: in the J/ψ sample, the cross-section fell to zero well below the momentum endpoint (see Fig. 3 of Ref. [1]).

The e^+e^- initial state being known, a simple rescaling of the J/ψ momentum gives the mass of the system recoiling against it in the final state:

$$M_{\text{recoil}}(\psi) = \sqrt{(\sqrt{s} - E_{\psi}^*)^2 - (p_{\psi}^*)^2} \quad (1)$$

An upper bound on momentum thus corresponds to a *lower bound* on the mass of the recoiling system. Studied in this way [4], the surprising conclusion (Fig. 1)

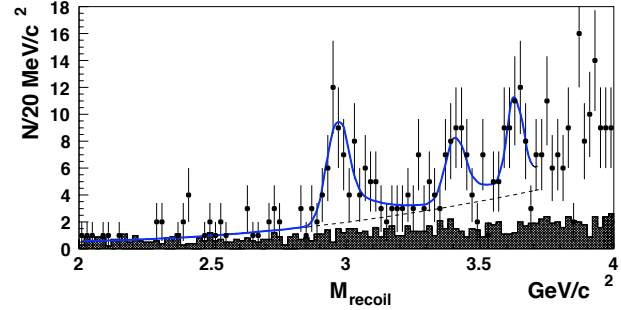


Figure 1: The mass spectrum of the unreconstructed (recoiling) system X in $e^+e^- \rightarrow J/\psi X$ production in early Belle data [4]. The curves show a fit to a series of charmonium states (solid) over a continuous component (dashed); the shaded histogram shows the distribution for events in the J/ψ mass sidebands. The charmonium lineshapes are broadened by initial state radiation: see the text.

was that the interaction $e^+e^- \rightarrow J/\psi X$ does not proceed if the mass of the recoiling system X is below $c\bar{c}$ threshold, while immediately above threshold there is significant two-body production, with $X = \eta_c, \chi_{c0}, \eta_c'$. Although familiar now, it is worth remembering how completely unexpected this result was at the time.

It was then accepted [5] that charmonium production at $\sqrt{s} \approx 10.6\text{ GeV}$ was dominated by the $e^+e^- \rightarrow \psi gg$ process, with a momentum spectrum extending to the kinematic endpoint and thus a M_{recoil} spectrum to low masses; $e^+e^- \rightarrow \psi c\bar{c}$ was an $\mathcal{O}(10\%)$ correction. An additional contribution from $e^+e^- \rightarrow \psi g$, where the charmonium develops from a colour-octet $c\bar{c}$ pair, was expected at momentum endpoint (low M_{recoil}). The contradiction with data led to reexamination of both theoretical and experimental methods.

In the recoil mass technique, the system X is not reconstructed and identification is thus indirect. Alternative explanations of the data have sprung from this limitation, while improvements to the method have focussed on partial reconstruction and constraints. The original analysis [4] already used a mass-vertex constraint in J/ψ reconstruction, improving M_{recoil} resolution by a factor of two. Contributions from QED processes are more troublesome. Initial-state radiation (ISR) leads to a high- M_{recoil} tail (typically model-

dependent) on the lineshape of any peak; more than four tracks are required to suppress contributions from other (low-multiplicity) QED interactions.

The leading alternative interpretation of the data relied on such a process: $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow \psi X$ [6]. While $e^+e^- \rightarrow \gamma^* \rightarrow \psi X$ production requires the second state to be even under charge conjugation, $\xi_C^X = +1$, the two-virtual-photon process allows $\xi_C^X = \pm 1$ and in particular permits $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow J/\psi J/\psi$. As only the $J/\psi \eta_c$ signal was statistically significant in the 2002 analysis [4], it was attractive to ascribe the peak (in part) to events with a second J/ψ . A more ambitious (and essentially mirror-image) proposal [7] was that $e^+e^- \rightarrow \psi gg$ did in fact dominate charmonium production, with the gluons sometimes coupling to a glueball state close to the η_c mass.

These and other interpretations were effectively ruled out by an updated Belle analysis [8], using 155 fb^{-1} of data and techniques designed to discriminate between the theoretical options. Three $e^+e^- \rightarrow \psi \eta_c$ events were fully reconstructed, to be compared with the 2.6 ± 0.8 expected from the inclusive yield. The recoil mass scale was also calibrated using $e^+e^- \rightarrow \gamma_{ISR} \psi'$ events and found to have a bias of less than 3 MeV, ruling out confusion between η_c and J/ψ . Attempts to include $e^+e^- \rightarrow \psi \psi^{(\prime)}$ components in the recoil mass fit resulted in negative yields, and restrictive upper limits on their contribution (see Fig. 2, upper plot). An eventual confirmation by BaBar [9] found comparable results (lower plot).

Belle also performed an angular analysis of $J/\psi \eta_c^{(\prime)}$ and $J/\psi \chi_{c0}$ events. The distinctive forward peak in J/ψ production angle ($\cos \theta_{\text{prod}} \rightarrow 1$) predicted by the two-virtual-photon model for $J/\psi J/\psi$ (Fig. 2 of Ref. [6]) was not seen in data: results for all three states were consistent with shapes $1 + \alpha \cos^2 \theta$, and equal coefficients for production- and helicity-angle distributions (see Table I) as expected for a single virtual photon. The $J/\psi \eta_c^{(\prime)}$ fits were consistent with $\alpha = +1$ (P-wave production) as required by η_c quantum numbers, and strongly disfavoured the -0.87 expectation for a spin-zero glueball [7]. One- rather than two-virtual photon production (or the glueball explanation) is thus favoured by all experimental tests.

Table I Coefficients from fits of the function $1 + \alpha \cos^2 \theta$ to J/ψ production (θ_{prod}) and helicity angle (θ_{hel}) data at Belle [4], for $e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}}$. See the text for results under the constraint $\alpha_{\text{hel}} = \alpha_{\text{prod}}$, and the expectation.

$(c\bar{c})_{\text{res}}$	α_{prod}	α_{hel}	$\alpha_{\text{hel}} \equiv \alpha_{\text{prod}}$	expectation
η_c	$+1.4_{-0.8}^{+1.1}$	$+0.5_{-0.5}^{+0.7}$	$+0.93_{-0.47}^{+0.57}$	+1 (P)
χ_{c0}	-1.7 ± 0.5	$-0.7_{-0.5}^{+0.7}$	$-1.01_{-0.33}^{+0.38}$	-1 (S)
η_c'	$+1.9_{-1.2}^{+2.0}$	$+0.3_{-0.7}^{+1.0}$	$+0.87_{-0.63}^{+0.86}$	+1 (P)

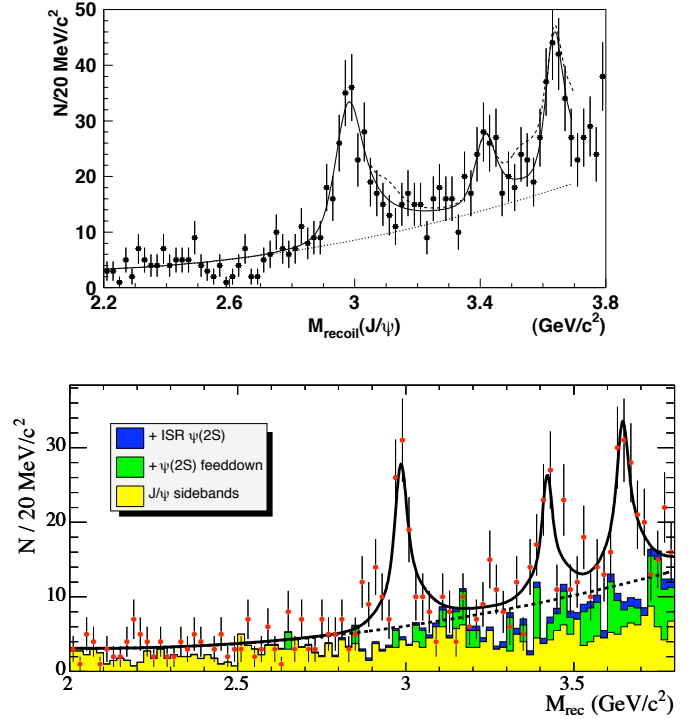


Figure 2: Baseline $e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}}$ results from Belle ([8], upper plot), and the confirmation from BaBar ([9], lower plot). In the upper plot the dashed line shows the upper limit contribution from final states where the fitted yield is insignificant or negative: $J/\psi (J/\psi, \chi_{c1,c2}, \psi')$.

3. Baseline results

Belle [8] and BaBar [9] measurements of $e^+e^- \rightarrow \psi^{(\prime)} (c\bar{c})_{\text{res}}$ cross-sections are summarised in Table II: with competing explanations excluded, and reasonable agreement between the two experiments, these results are no longer in serious dispute. Remarkably, there seems to be no suppression of radially-excited states: cross-sections for $\psi \eta_c$, $\psi \eta_c'$, $\psi' \eta_c$, and $\psi' \eta_c'$ are all comparable. This presumably contains some hint as to the production mechanism.

Low-order perturbative calculations, as embodied in nonrelativistic quantum mechanics (NRQCD, [10, 11, 12]) underestimate the cross-sections by an order of magnitude or more; the discrepancy is reduced, but not removed, when relativistic corrections are taken into account [10]. Neither are other features of the data well-explained: NRQCD predicts $\alpha \simeq +0.25$ for $e^+e^- \rightarrow J/\psi \chi_{c0}$ [10], disfavoured by the Belle analysis (Table I), which prefers pure S-wave production.

A calculation in the light-cone formalism [13], however, appears to match at least the $J/\psi \eta_c$ cross-section. A variety of theoretical approaches are currently being pursued, and it is no longer easy to characterise the issues at stake: on comparison of NRQCD and light-cone estimates, see for example the very ex-

Table II Double-charmonium production cross-sections from Belle and BaBar, with theoretical pre- and post-dictions. Due to background-suppression criteria, the experiments report effective cross-sections for the case where the unreconstructed state $(c\bar{c})_{res}$ decays to at least 2 (“> 0”) or 4 (“> 2”) charged tracks, and thus underestimate the cross-section.

$\sigma(e^+e^- \rightarrow \psi(nS) (c\bar{c})_{res})$ [fb]		$(c\bar{c})_{res}$		
		$\eta_c(1S)$	χ_{c0}	$\eta_c(2S)$
$\psi(2S), \times \mathcal{B}_{>0}$	Belle [8]	$16.3 \pm 4.6 \pm 3.9$	$12.5 \pm 3.8 \pm 3.1$	$16.0 \pm 5.1 \pm 3.8$
$\psi(1S), \times \mathcal{B}_{>2}$	Belle [8]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
	BABAR [9]	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
$\psi(1S)$	Braaten and Lee [10]	3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52
... with relativistic corrections [10]		$7.4^{+10.9}_{-4.1}$	–	$7.6^{+11.8}_{-4.1}$
	Liu, He, and Chao [11]	5.5	6.9	3.7
	Zhang, Gao, and Chao [12]	14.1	–	–
	Bondar and Chernyak [13]	33	–	–

tended discussion in Ref. [14]. Analysis of the merits of this theoretical work is outside the scope (and competence) of this review.¹ It does however seem clear that experimental work is still driving, rather than being directed by, theoretical studies.

4. The new cutting edge: states above open-charm threshold

Active experimental work has now shifted to the case where the system recoiling against the ψ is above open-charm threshold. Even allowing for the various $e^+e^- \rightarrow D^{(*)}\bar{D}^{(*)}$ continuum components in fitting the inclusive $M_{recoil}(\psi)$ spectrum, Belle found a 5.0σ peak at (3936 ± 14) MeV (Fig. 1 of Ref. [16]). The background under this peak (called $X(3940)$) being too large for further detailed study, Belle explicitly reconstructed a D-meson and then considered cases where the remaining system was close to the D or D^* in mass: $M_{recoil}(\psi D) \approx m_{D^{(*)}}$. Constraining such cases to match the $D^{(*)}$ mass also improved the $M_{recoil}(\psi)$ resolution. This allowed the reconstruction of a clear $X(3940) \rightarrow D^*\bar{D}$ peak, and an upper limit on the same structure in $D\bar{D}$ (Fig. 3 of [16])

Belle has released an updated analysis [17] based on systematic use of this $D^{(*)}$ -tagging technique. Fig. 3 shows the $M_{recoil}(\psi D^{(*)})$ spectrum for 693fb^{-1} of data, after reconstruction and mass-constraint of the J/ψ , and then a D^0 , D^+ , or D^{*+} meson. A simultaneous fit with the $D^{(*)}$ -mass sidebands is performed: clear and significant peaks are seen, corresponding to processes $e^+e^- \rightarrow \psi D\bar{D}$, $\psi D^*\bar{D}$, and $\psi D^*\bar{D}^*$.

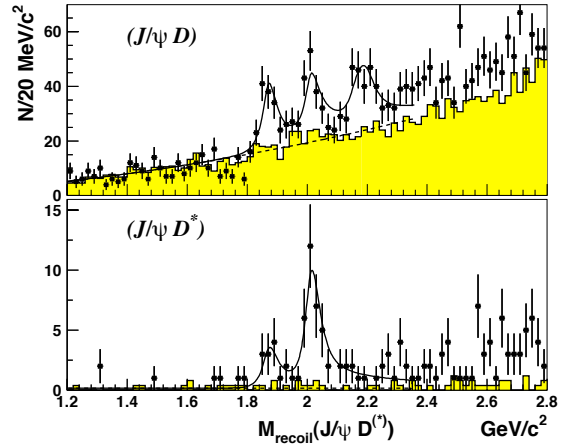


Figure 3: The mass of the system recoiling against fully-reconstructed J/ψ and D (upper plot) or D^{*+} (lower plot) mesons at Belle [17]. The shaded histogram shows the distribution in $D^{(*)}$ -mass sidebands: the fitted curve is discussed in the text.

Monte Carlo study shows that we indeed expect these processes to be reconstructed in this way, with recoil mass resolution of about 30 MeV: smaller than the difference in D and D^* masses. Disjoint samples $|M_{recoil}(\psi D^{(*)}) - m_{tag}| < 70$ MeV where the unreconstructed system is tagged as a D or a D^* are thus selected (ISR leads to a 10% $\psi D\bar{D} \rightarrow \psi D\bar{D}^*$ cross-feed), and $M_{recoil}(\psi D^{(*)})$ is then constrained to the mass of the tagged meson. This improves the resolution on $M(D^{(*)}\bar{D}^{(*)})$ by a factor of 3–10: results for the three samples are shown in Fig. 4. Peaks above the background are seen near threshold in each sample.

Combinatorial backgrounds are taken into account via simultaneous fits to the data in the reconstructed $D^{(*)}$ -mass signal and sideband regions. The excess over background is fitted with the sum of a threshold function to represent non-resonant $e^+e^- \rightarrow$

¹We note that a theoretical analysis has appeared since the workshop [15], claiming that the discrepancy in the $J/\psi \eta_c$ cross-section between NRQCD and experiment is now resolved.

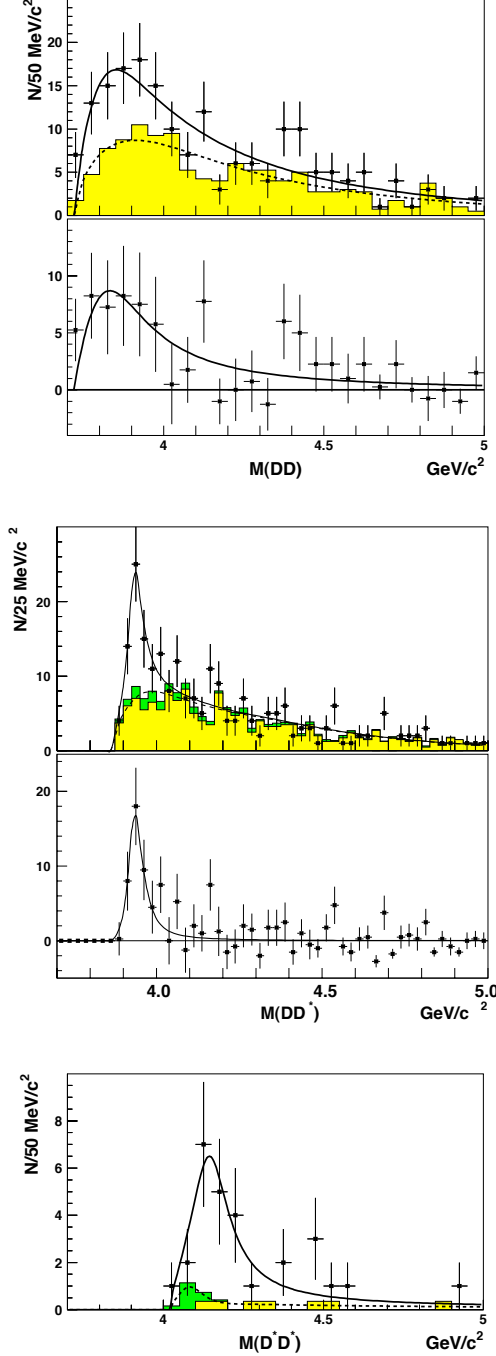


Figure 4: $M(D^{(*)}\bar{D}^{(*)})$ spectra for $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$ events at Belle [17], where the first D-meson is explicitly reconstructed, and the associated D-meson is recovered via recoil mass selections and constraints: (upper) DD , (middle) DD^* , and (lower) $D^*\bar{D}^*$ samples are shown. Distributions in the reconstructed $D^{(*)}$ -mass sidebands are shown in yellow, and reflections (middle) $DD \rightarrow D\bar{D}^*$ and (lower) $DD^* \rightarrow D^*\bar{D}^*$ in green. The solid curves show the fits described in the text, and the dashed curves show their combinatorial background and reflection components. The second panel in the upper and middle plots shows the data and fit with these components subtracted.

Table III Resonant enhancements in $e^+e^- \rightarrow \psi D^{(*)}\bar{D}^{(*)}$ production at Belle [17]. The ψ and the meson shown are fully reconstructed and then refitted under a mass constraint: the remaining meson is identified as discussed in the text.

Final state	$D\bar{D}$	$D\bar{D}^*$	$D^*\bar{D}^*$
Reconstructed	D	D	D^*
Resonant term	—	$X(3940)$	$X(4160)$
Mass (MeV)	3878 ± 48	$3942^{+7}_{-6} \pm 6$	$4156^{+25}_{-20} \pm 15$
Width (MeV)	347^{+316}_{-143}	$37^{+26}_{-15} \pm 8$	$139^{+111}_{-61} \pm 21$
Significance	4.4σ	6.0σ	5.5σ
Fit behaviour	unstable	stable	stable
$\sigma(e^+e^- \rightarrow \psi X)$	—	$13.9^{+6.4}_{-4.1} \pm 2.2$	$24.7^{+12.8}_{-8.3} \pm 5.0$
$\times \mathcal{B}_{D^{(*)}\bar{D}^{(*)}}$ (fb)	—		

$\psi D^{(*)}\bar{D}^{(*)}$ production, and an S-wave relativistic Breit-Wigner. In all cases the threshold term is insignificant, and a significant Breit-Wigner peak is seen. In $M(DD)$ the peak is broad, and the fit unstable against variations of its conditions; in $M(DD^*)$ and $M(D^*\bar{D}^*)$ the fit is stable and the resonant peak significant at over 5σ . Various cross-checks are performed, including Monte Carlo and data tests of the background shape in $D^{(*)}$ -mass sideband and signal regions; study of charged- and neutral-D subsamples; and fitting of events with reconstructed D^* , and associated \bar{D} : the latter obtains results consistent with the $J/\psi D\bar{D}^*$ analysis of Fig. 4 (middle), but with lower efficiency and significance. Parameters for the resonant enhancements are summarised in Table III.

The $X(4160)$ enhancement has not previously been reported. The $X(3940)$ mass and yield results are consistent with those of the earlier analysis [16], while the width is larger than the published value of (15.1 ± 10.1) MeV: a likelihood function non-parabolic in the width parameter had been noted in that case, with a 52 MeV upper limit at 90% confidence. The corresponding limit in the new analysis is $\Gamma < 76$ MeV.

Cross-sections for $J/\psi X(3940)$ and $J/\psi X(4160)$ production (Table III, last row) are in the 20 femto-barn class, as for all the significant $e^+e^- \rightarrow \psi^{(\prime)}(c\bar{c})_{res}$ processes seen to date.

5. Sidelines

The concentration on experimentally fruitful problems — establishing and measuring quasi-two-body processes $e^+e^- \rightarrow \psi^{(\prime)}(c\bar{c})_{res}$ — has led to a relative neglect of inclusive $e^+e^- \rightarrow \psi^{(\prime)}X$ studies. The 2002 Belle analysis [4] established the fraction

$$\frac{\sigma(e^+e^- \rightarrow \psi c\bar{c})}{\sigma(e^+e^- \rightarrow \psi X)} = 0.59^{+0.15}_{-0.13} \pm 0.12 \quad (2)$$

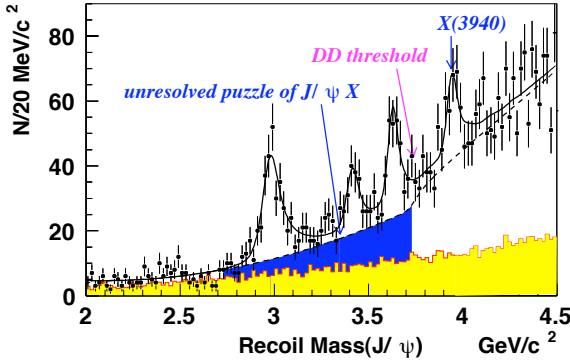


Figure 5: Inclusive $e^+e^- \rightarrow J/\psi X$ data, showing the combinatorial background (yellow) and non- $J/\psi (c\bar{c})_{res}$ contributions (blue) below open-charm threshold. (Adapted from a figure by P. Pakhlov.)

using the following method: reconstruction and mass-constraint of J/ψ , and then an associated $D^{(*)}$ -meson; rejection of contamination from $e^+e^- \rightarrow B\bar{B}$ events using momentum requirements; and a two-dimensional fit to obtain $\psi D^{(*)} X$ yields (see Fig. 2 of Ref. [4]). The cross-section thus obtained is model-dependent, relying on simulated $c\bar{c} \rightarrow D^{(*)} X$ fragmentation by PYTHIA to establish efficiencies. There has been no published update of this remarkable result.

(Model-independent but since-unpublished Belle results were presented to the Quarkonium Working Group in 2002, relying instead on counting of D^0 , D^+ , and all ground-state charmed hadrons under minimal cuts. Resolution was similar, with a lower limit on the $J/\psi c\bar{c}$ fraction of 0.48 at 95% confidence.)

A complementary problem is the nature of $e^+e^- \rightarrow J/\psi X$ production by processes other than $J/\psi c\bar{c}$. Such production does seem to occur: there is a continuous component in inclusive recoil mass spectra (Fig. 5) in excess of background, below the open-charm threshold. The mystery is why this component — due to the $e^+e^- \rightarrow \psi g$ process? — should obey the $c\bar{c}$ threshold. A problem for experimental study here is the lack of theoretical guidance: predictions for the various $e^+e^- \rightarrow \psi X$ processes that so pre-occupied the original Belle [1] and BaBar [2] analyses have been discredited, but new predictive studies have not taken their place. Such work is overdue.

6. Summary

The period of fundamental doubt about double charmonium production is now over. Questions concerning the experimental method have been addressed, and the potential for confusion by $e^+e^- \rightarrow \gamma^* \gamma^* \rightarrow J/\psi X$ or other more exotic processes has been excluded [8]. And the fear that some untraceable mistake had been made is effectively dispelled by BaBar's confirmation [9] of the Belle results [4].

Those results establish that $e^+e^- \rightarrow \psi c\bar{c}$ dominates charmonium production in the continuum at $\sqrt{s} \approx 10.58$ GeV, while $\psi^{(\prime)} (c\bar{c})_{res}$ cross-sections are at the 20 fb level, with no suppression of radially excited states. Recent work shows that prominent resonant contributions continue above open-charm threshold, with similar cross-sections; this process is proving fruitful in the search for new hidden-charm states.

The ball now lies in the court of theory. Interpretive work on the new states $X(3940)$ and $X(4160)$ is already underway, but a predictive account of $e^+e^- \rightarrow \psi^{(\prime)} X$ amplitudes is still lacking. An advantage of the NRQCD approach is its pretension to universal application: at the Tevatron, for example, and the LHC. We await an accurate account of double-charmonium production in e^+e^- annihilation that can also embrace quarkonium production at other facilities.

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